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A SERVO CONTROLLED RAPID RESPONSE ANTI-G VALVE

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18. SUPPLEMENTARY NOTES

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Current anti-G —

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hi-G Protection
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Centrifuge Evaluation
M-1 Straining Maneuver
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Aircrewman exposed to high accelerative forces associated with air combat maneuvers, air-to-ground maneuvers, and missile evasive maneuvers, suffer failures in their vision and cognitive processes due to the inability of their circulatory system to supply blood and hence oxygen to the brain. To aid the aircrewman in combating the effects of these forces, anti-G suits are provided. These suits inflate under control of an anti-G valve and apply pressure to the abdominal and leg areas to prevent blood pooling in the lower portions of the body. The

(continued)

20. Continued

Current anti-G valves employ a spring and mass construction ~~method~~ which regulates air flow to the suit in direct proportion to the amount by which the applied G force exceeds a nominal 2G breakout force. This mechanical method, however, does not permit rapid filling of the suit required during high onset G profiles generated by high performance VA/VF aircraft.

This ~~The Naval Air Development~~ Center has designed, constructed, and tested a prototype servo controlled rapid response anti-G valve system. This system, which employs a pressure transducer located in the valve outlet line but modified to represent the pressure in the anti-G suit as the feedback signal, is capable of pressurizing the suit on a schedule which closely coincides with that of a rapidly applied G profile. In addition, this new valve is capable of improved system reliability, and of incorporating a number of outstanding features.

A series of manned tests were conducted on the NAVAIRDEVCEN human centrifuge to compare the protection provided to relaxed and straining subjects exposed to rapid onset G-profiles by the current mechanical valve system and the servo valve system. The servo valve system proved superior to the mechanical ~~valve~~ system exhibiting an average 0.5 G tolerance improvement when subjects were in a relaxed state and an average 1.3 G tolerance improvement when the subjects were in an M-1 straining state.

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INTRODUCTION AND BACKGROUND

The current generation of fighter/attack aircraft has aerodynamic, structural, and propulsion systems tailored for high energy maneuvering. This high maneuvering capability provides the pilot with the tactical advantage required to maintain air superiority but challenges his ability to fully use this capability because of the high accelerative forces associated with it. These forces effectively increase the weight of the pilot's blood which is equivalent to lengthening his cardiac cerebral hydrostatic column; this places a heavy burden on his heart as it attempts to overcome the weight of this column and supply oxygenated blood to the brain. Failure of the heart to perform this function causes the pilot to experience a loss of vision, a failure of cognitive processing, and eventually a loss of consciousness (LOC).

To increase the pilot's ability to withstand these accelerative forces, he is provided with an anti-G suit containing bladders which inflate under control of an anti-G valve and applies pressure over the abdominal and leg areas. Further protection is provided if the pilot performs a straining maneuver in combination with the suit pressurization. Critical to the amount of protection provided by these actions, however, is the time at which they occur relative to the G profile. If the suit is pressurized too early, the pilot may experience pain and discomfort which may inhibit his straining maneuver. If it is pressurized too late, blood pooling in the lower extremities may have already occurred and created a condition which the eventual suit pressurization may not be able to overcome. Ideally, the suit should be pressurized in synchrony with the increasing G profile.

A standard production anti-G valve currently in use by the fleet is the ALAR P/N 8000A. This model, hereafter referred to as "standard", has had no improvements in its basic design since it was developed during World War II. The valve is basically a spring loaded mass system which controls the pressure in the anti-G suit by the action of the applied G force. This force opens and closes the valve by displacing the mass, the opening being directly proportional to to the amount by which the longitudinal component of that force (G_z) exceeds a nominal 2 G breakout. This open-loop proportional method of control introduces an inherent lag between the applied G force and the suit pressure which is particularily noticeable during high rates of G onset, a common occurrence in modern high performance aircraft. The pilot is thus left with the task of combating the high G without assistance from his suit. This reduces his tolerance to the G, adds to his stress and fatigue, and diminishes the mission effectiveness of his aircraft/weapons system. Pilots have been known to use their elbow or log book to force the valve to respond faster.

Frictional forces introduce an additional lag in the response of the standard system during high angle of attack (α) maneuvers because of the transverse forces involved, and during high side slip (β) maneuvers because of the lateral forces involved. Nor does the valve effectively compensate for large fluctuctions which may occur in the supply pressure and for variations in the suit pressure occasioned by rapid inhalation during an M-1 maneuver. Also, the standard valve has had an excessive number of malfunctions which have considerably reduced the reliability and effectiveness of the anti-G system. Studies indicate that these malfunctions are due mainly to corrosion and the deposition of contaminants from the engine bleed air used in the operation of the valve (reference 1).

A new anti-G valve is needed, therefore, which has improved reliability and which pressurizes the aircrewman's anti-G suit on a schedule which closely coincides with his normal G profile. Furthermore, this schedule should be achieved independent of the rate of G onset, the amount by which the valve is misaligned with the resultant G vector, or fluctuations in the supply pressure.

In response to this need, two different concepts in anti-G valve design have recently been developed and tested. The USAF School of Aerospace Medicine has developed a Hi-Flow Ready Pressure (HFRP) anti-G valve which is a modification of the current standard ALAR valve (reference 2). This valve achieves an increase in the rate of G-suit pressurization by: a) preinflating the suit to 0.2 psi prior to an increase in G (called "Ready Pressure"); and b) increasing the capacity of the air flow through the anti-G valve by increasing the sizes of several ports within the valve (called "Hi-Flow").

This suit prepressurization can be uncomfortable for pilots for prolonged periods of time (reference 3), and will therefore require that provisions be included for an on/off switch, probably pilot activated, as suggested in reference 2. The 50% increase in air flow capacity, 15 SCFM to 22 SCFM, achieved by Hi-Flow, is considerably less than could be obtained if not restricted to modifying an existing valve. Also, the basic problems associated with the standard valve, previously mentioned, remain and little possibility exists for adapting this valve to include new features. The Naval Air Development Center, on the other hand, has designed, constructed, and tested an entirely new anti-G valve system (references 4 and 5) which is servo controlled. This valve is sufficiently responsive to enable it to control the suit pressure in close synchrony with the increasing G profile without the requirement for prepressurization, even under large lateral and transverse loads or with large fluctuations in the supply pressure. In addition, this new valve is designed to provide improved system reliability and is capable of incorporating a number of desirable features. This paper describes the design of this new servo controlled rapid response anti-G valve and the results of the system performance and system evaluation tests.

DESCRIPTION

A block diagram of the servo controlled anti-G valve system is shown within the dotted lines of figure 1. The opening of the valve is controlled by the amplified voltage difference between the output of the accelerometer and the suit pressure transducer. The gain of the amplifier is adjusted for maximum loop stability and minimum pressure lag. This valve controls a regulated and filtered air supply to a volume booster which in turn controls the volume of air supplied to the anti-G suit. The booster has the capacity of supplying up to 40 SCFM of air, or more than double that of the standard valve.

In an initial version of the servo valve system, the feedback signal was obtained from a pressure transducer inserted through a sealed opening in the suit. If this version were adopted for fleet use, however, it would require costly modifications to all anti-G suits. A second version has been adopted, therefore, which locates the feedback transducer at the outlet of the valve but modifies its output voltage with a time delay circuit to better compensate for the pressure lag in the suit. This version effectively closes the control loop between the accelerometer and the suit pressure and permits the packaging of the complete system in a single unit while providing an adjustable parameter for optimizing system performance. A relief valve is placed in the valve outlet line to prevent suit pressurization above 11 psi.

SYSTEM PERFORMANCE

The servo anti-G valve system is designed to control the pressure in the aircrewman's anti-G suit in accordance with the following formulae:

$$
\begin{aligned}
P &= 0 & ; \quad & G_z \leqslant 1.5 \\
P &= 1.5\,(G_z - 1) & ; \quad & 1.5 < G_z \leqslant 8.3 \\
P &= 11 & ; \quad & G_z > 8.3
\end{aligned}
$$

Where G_z is the longitundinal acceleration on the aircrewman in G units and P is the pressure in his anti-G suit in psig.

The ability of the valve system to meet these requirements during rapidly applied G in an aircraft environment, however, is of prime concern. This was determined through a series of dynamic response tests using the test set-up shown in figure 1. Here the size (3/8", O.D.) and length (8 ft.) of the air supply lines and the 5/8" anti-G suit connector hose were chosen to approximate the conditions which exist in the F-14 aircraft. The minimum supply pressure required to obtain the data shown was 50 psig or 36 psig if 1/2" O.D. tubing were used in the supply line. The anti-G suit, a CSU-15/P, size-large regular, was mounted on a torso dummy.

The results of the dynamic response tests are shown in figures 2 and 3 for two configurations of the servo valve. Here, pressure time histories recorded in both the valve outlet line, Po, and in the suit bladder, Ps, are shown in response to a 4 G, 3 second haversine G profile (1.5 second rise time). The first configuration used a feedback voltage derived from a pressure tranducer located in the valve outlet line and the pressure at that point faithfully follows the G profile after the 1.5 G breakout force (figure 2). The suit pressure on the other hand lags the G profile by approximately 0.5 seconds.

The system performance of the servo valve was further improved in the second configuration in which the tranducer feed back voltage was modified with a time delay circuit to simulate the suit bladder pressure. This permitted the pressure at the valve outlet to be over-driven, thereby reducing the lag between the G profile and the suit pressure to 0.2 seconds as seen in figure 3. For comparison purposes, suit pressure time histories with the standard valve in control are shown in both figures 2 and 3. In order to show the most favorable response of the standard valve and to draw attention primarily to the huge lag in the suit pressure response time, the scaling was increased to match that of the servo valve. An additional response curve was generated for the second servo valve configuration and shown in figure 3, with the suit prepressurized to 0.05 psig. Although this effectively eliminated any pressure lag between the suit pressure and the G profile, this minor improvement in system response does not appear to warrant the additional system complexities and pilot discomfort which the requirement for prepressurization would entail.

The servo controlled anti-G valve system thus offers a major improvement in system response over the standard valve without the requirement for prepressurization. This improvement is obtained primarily by replacing the inertia driven proportional method of control with a tight servo loop method and by increasing the effective capacity of the valve. Additionally, the positive action of the servo controlled valve insures no degradation in system performance when the valve is misaligned with the G vector during high angle-of-attack or high side slip maneuvers, or when large fluctations in the supply pressure (50 to 300 psig) occur.

Also, since it is electronically controlled, the servo valve system is uniquely adaptable to incorporate the following desirable features:

1. Further optimization of pressure schedule, if required, to maximize protection and minimize pilot discomfort.

2. Anticipatory pressurization of the suit by obtaining the valve control signals directly from the on-board computer.

3. Pressure scaling controlled by seat back angle to prevent suit over pressurization when pilot is partially supinated.

4. Generation of pulsatile, periodic, or vibrating suit pressures to relieve tension during long flight hours or to enhance G protection.

5. Delay in the pressurization of different segments of the suit to achieve "milking" action to further enhance G protection.

SYSTEM EVALUATION

Although the dynamic response tests have shown that the performance of the servo anti-G valve is vastly superior to that of the standard anti-G valve, it is obviously desirable to determine whether this improved performance translates into improved pilot G protection.

Toward this end, human tolerance experiments were conducted on the NAVAIRDEVCEN centrifuge to compare the amount of protection provided by the anti-G suit when the servo anti-G valve was in control versus when the standard anti-G valve was in control and with the subjects in either the relaxed or straining (M-1) state.

Five volunteers, four male and one female, ages 22 to 39, participated in this study. All had previous experience on the centrifuge and had undergone routine training in performing an effective M-1 straining maneuver. This maneuver is a conscious effort by the subject to crouch in his seat and perform a sequence of repeated muscular activities involving rapid inhalation, contracted muscles in the arms, legs, and torso, and protracted exhalation against a partially closed glottis. When properly performed, the M-1 maneuver has proven to provide a substantial increase in the subject's G tolerence (references 6 and 7).

The G profiles used during the tests are illustrated in figure 4. Each run started from the 1.03 G level and accelerated to a plateau G level in 3 seconds (a haversine shape). The time at plateau was 15 seconds unless terminated earlier by the attending flight surgeon or the subject himself. Each series of runs started at a plateau level of 2.5 G with subsequent runs increased by 0.5 G until the subject's G tolerence limit was reached. By previous agreement, 8 G was not to be exceeded. This type of G profile was chosen over one in which the G onset rate remained constant from one run to the next because it eliminates time of G exposure as a variable when the G plateau is varied. The G onset rate for the 8 G profile was 4.5 G/sec.

The G tolerence limit used during these experiments was the G level at which a subject was able to sustain the complete G profile (3 second rise time plus 15 second plateau time) without loss of peripheral vision (PLL). To increase the G tolerence limit accuracy beyond that of the 0.5 G increment used here, the following formula was used to extrapolate upward from the highest G tolerance limit measured.

$$G_{TL} = G_{TL1} + \frac{\Delta T}{T}(\Delta G)$$

WHERE

G_{TL} = Subject's G tolerance Limit

G_{TL1} = Highest G level tolerated for complete G profile.

T = Time of G profile, rise time plus plateau time (18 seconds)

ΔT = Time from start of G before PLL occurs.

ΔG = Incremental G above G_{TL1}

Thus, if a subject has sustained a 4.5 G run and experiences PLL after 7 seconds at the 5 G level, his G tolerance limit is calculated to be

$$G_{TL} = 4.5 + (10/18)\ (0.5) = 4.78$$

Peripheral light loss (PLL) is one of the early indications of the effects of G on a subject and, if accurately measured, provides a harmless and convenient end-point for comparing various protective methods. Since comparative protection rather than ultimate protection is the prime interest here, the G level end points occur at a somewhat lower level than the subjects were capable of sustaining; i.e. if blackout or LOC were used as end-points.

Each subject's PLL end-point for the many conditions included in this investigation, was obtained through the use of a recently designed light bar (reference 5). This light bar contains 60 pairs of red light emitting diodes (LEDs) symmetrically arranged about the subject's head on a semicircular bar, 160 cm. in diameter, at intervals of 1.5 degrees about a central while incandescent light. The amount of force the subject applies to a control stick determines which pair of LEDs are illuminated at a given time. The subject's task is to keep a pair of LEDs illuminated at a subjectively determined constant brightness in the outer limits of his field of vision. When his field of vision dims under acceleration, the subject reduces the pressure on the control stick, and the angle subtended by the illuminated pair of LEDs is reduced. By programming the device to automatically activate a centrifuge stopping sequence when the subject tracks his peripheral vision to within 30 degrees of the central light, an accurate and reproduceible measure of a trained subject's PLL end-point can be measured.

A closed-circuit, low-light level, video camera mounted in the centrifuge gondola permitted the attending flight surgeon to view the subject continuously throughout the experiment. In addition, the flight surgeon monitored doppler recordings of blood-flow velocity in the superficial temporal artery, two channels of ECG, respiration, and intermittent measures of blood pressure as obtained by means of a remotely activated external cuff on the subject's left arm. The doppler pulse signal was used as a secondary criterion to the light bar tracking, with the flight surgeon terminating a run when a 3-second cessation of the pulse was observed.

Preliminary analyses of the blood-flow data indicate that the rapid pressurization of a subject's anti-G suit, achieved when the servo valve is in control, considerably reduces the large initial drop of blood-flow which normally occurs in the superficial temporal artery during the early stage of a high-onset G profile (figure 5) and which is generally acknowledged to be responsible for causing the subject to experience PLL. This effect is not achieved when the standard anti-G valve controls the suit pressure and is considered the basic reason why the servo valve provides an increase in G protection over the standard valve.

RESULTS AND DISCUSSION

Individual and mean PLL G tolerence limits and G protection values for each experimental condition used in this study are summarized in table I and graphically illustrated in figure 6. The anti-G suit is observed to increase the mean G tolerance of a subject in a relaxed state from 3.1 G to 3.9 G when the pressure is controlled by a standard valve and to 4.4 G when the pressure is controlled by the servo valve. Thus the servo valve increases the protective value of the enit-G suit by approximately 0.5 G for a relaxed subject.

For a subject performing the M-1 maneauver in conjunction with the inflation of his anti-G suit, table I also shows that the servo valve increases the effectiveness of this maneuver. The M-1 G tolerance values for subject S5 is not included in this table because they exceed the prearranged 8 G limit set for the program.

Mean G tolerance is seen to increase from 3.1 G to 4.3 G when subjects perform the M-1 maneauver alone, to 6.0 G when they perform the maneuver in conjunction with the inflation of their anti-G suit controlled by a standard valve, and to 7.3 G when the standard valve is replaced by the servo valve. The total G protection provided by each of these three

techniques in order, therefore is, 1.2 G, 2.9 G, and 4.2 G, with the anti-G suit alone contributing 0.8 G and 1.3 G to the latter two values respectively. The servo valve, in comparison with the standard valve, thus provides an additional 1.3 G protection to a subject performing an M-1 maneuver in conjunction with the inflation of his anti-G suit. Although it would have been desirable to have used a larger number of subjects, paired t-tests show that the servo valve is significantly better than the standard valve under both relaxed ($P < .01$) and M-1 ($P > .05$) conditions.

Noteworthy in the results, is the observation that the total effect of combining these protective techniques is more than would be predicted by simply adding the protection provided by each technique individually. This seemingly synergistic effect is discussed by Cohen (reference 7) and depicted in table II as the Δ protection.

Cohen indicated that the anti-G suit and the M-1 maneuver may involve interactive and synergistic mechanisms. That is, the anti-G suit could provide a platform against which the M-1 can be performed with enhanced effectivensss. Thus, the more effective the anti-G suit, the more effective the M-1 maneuver.

The system performance study has demonstrated the superior performance of the servo valve without prepressurization, and the system evaluation study has shown a 0.5 G improvement in G tolerance over the standard valve for a relaxed subject and a 1.3 G improvement for a subject performing an M-1 maneuver. Also, subjective comments were highly positive throughout the experiments regarding the ability of the new valve to pressurize the suit "on schedule" with the G, with no complaints voiced concerning any pain or discomfort caused by too rapid pressurization of the suit. These results, along with other benefits discussed, provide sufficient evidence to warrant replacing the standard anti-G valve with the servo rapid response anti-G valve in current and future fighter/attack aircraft.

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TABLE I – G TOLERANCE (PLL) AND G PROTECTION

Conditions	Subjects					Tolerance		AGS Protec.		Significance	
	S1	S2	S3	S4	S5	Mean	SD	Mean	SD	Paired t-test	PHO
Relaxed											df=4
1. No AGS	2.75	3.29	3.31	2.75	3.40	3.10	.29				
2. St'd AGV	3.31	3.35	4.25	4.23	4.30	3.89	.46	.79	.52	3.37	.05
3. Servo AGV	3.81	3.85	4.49	4.83	4.78	4.35	.44	1.25	.55	5.06	.01
Servo vs STD	.50	.50	.24	.60	.45			.46	.13	7.76	.01
M-1											df=3
4. No AGS	4.39	4.82	3.83	4.22	*	4.32	.36				
5. St'd AGV	5.81	6.70	5.74	5.68	*	5.98	.42	1.67	.26	12.66	.01
6. Servo AGV	6.92	8.00	7.88	6.37	*	7.30	.68	2.98	.83	7.16	.01
Servo vs STD	1.11	1.30	2.14	.69				1.31	.61	4.30	.05

*End Points beyond program limits

TABLE II – SYNERGISTIC EFFECT OF AGS AND THE M-1 MANEUVER

Technique	Individual Protection G-units	Predicted Protection G-units (M-1)+ AGS	Actual Protection G-units (M-1)+ AGS	△ Protection G-units
M-1	1.2			
Std valve/AGS	0.8	2.0	2.9	0.9
Servo valve/AGS	1.3	2.5	4.2	1.7

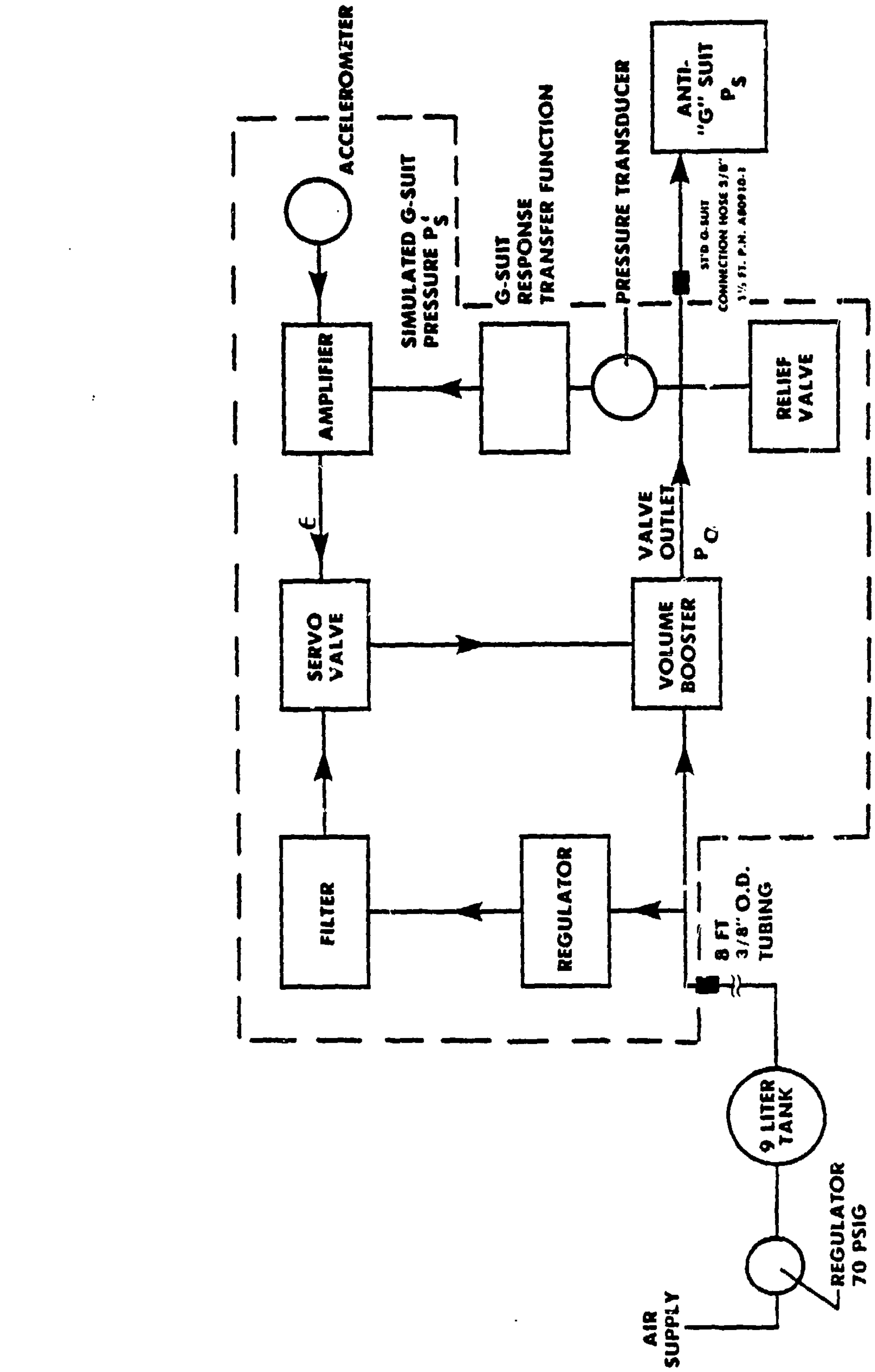

Figure 1. Block Diagram — Servo Anti-G Valve and Test Setup.

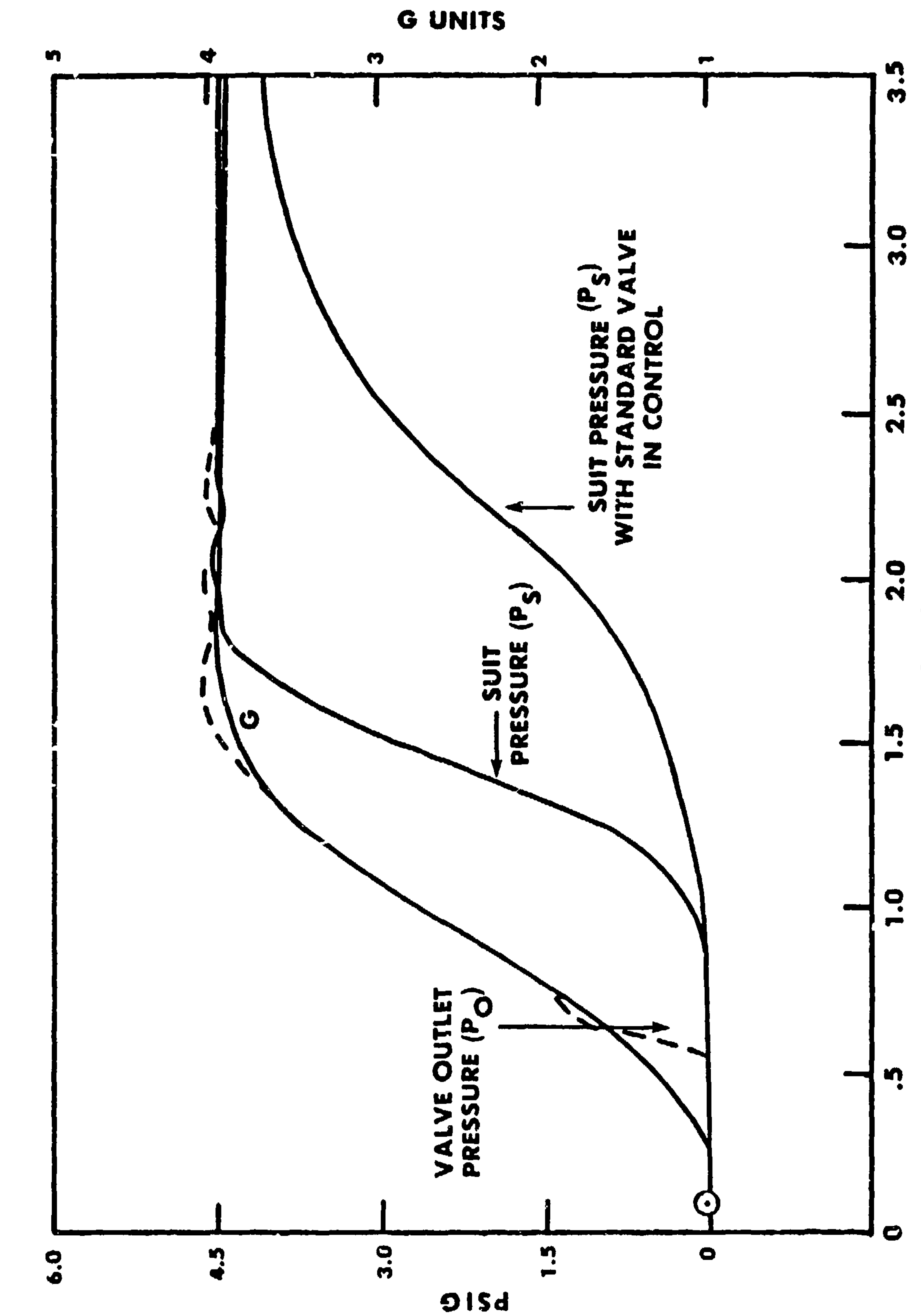

Figure 2. Pressure — Time Histories Using P_O As Feedback In Servo Valve.

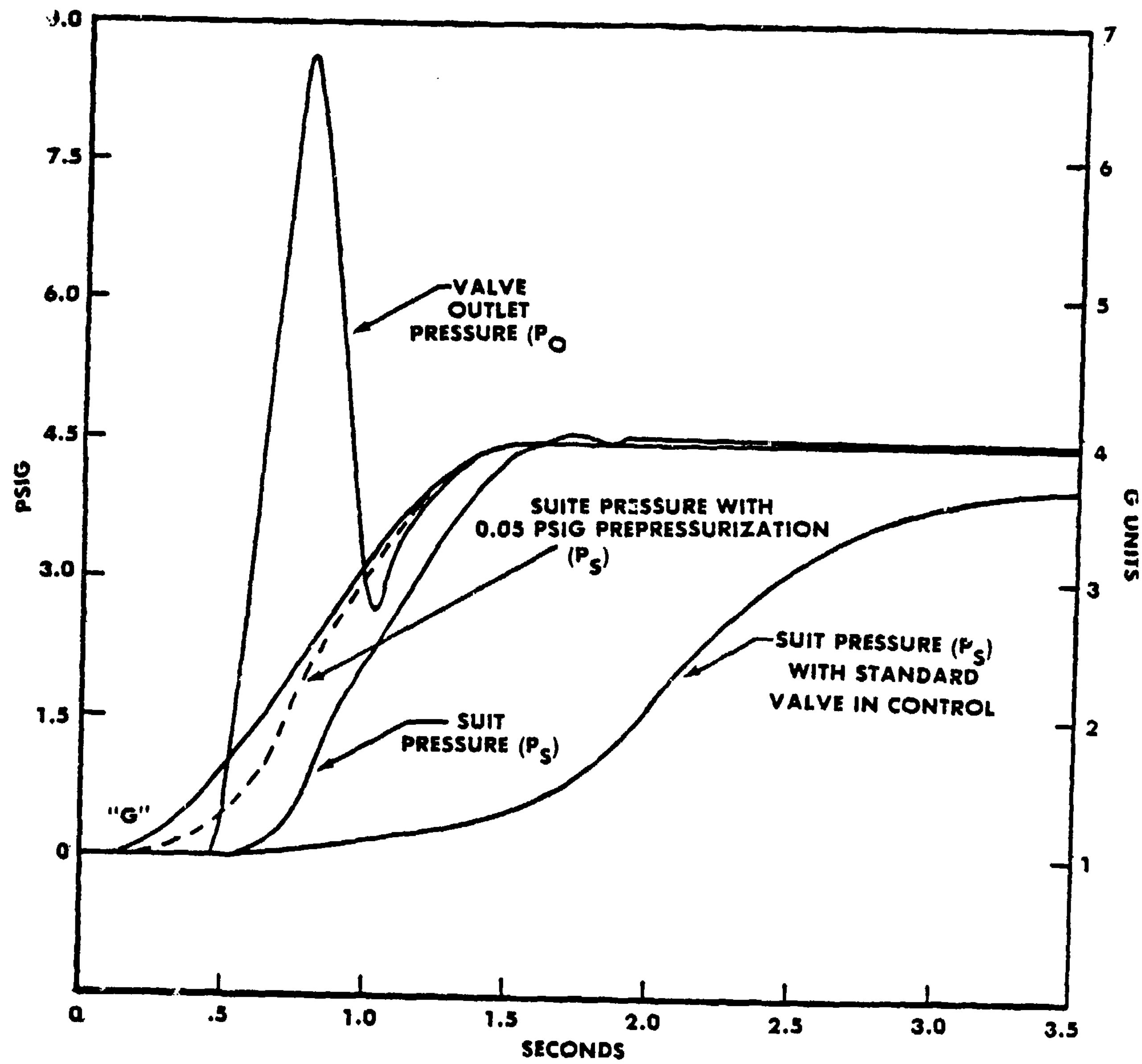

Figure 3. Pressure – Time Histories Using P_S As Feedback in Servo Valve.

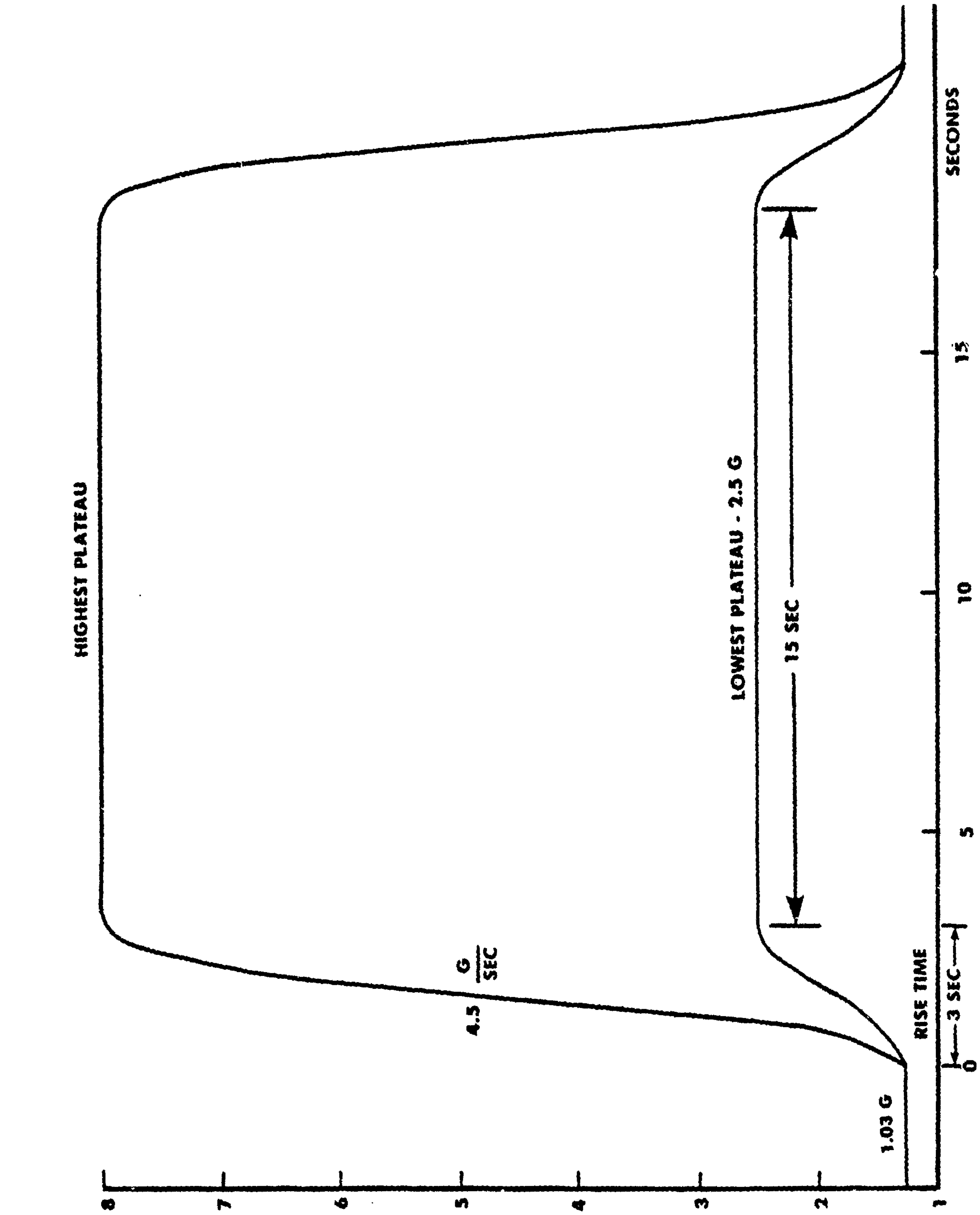

Figure 4. G Profiles Used In The Study.

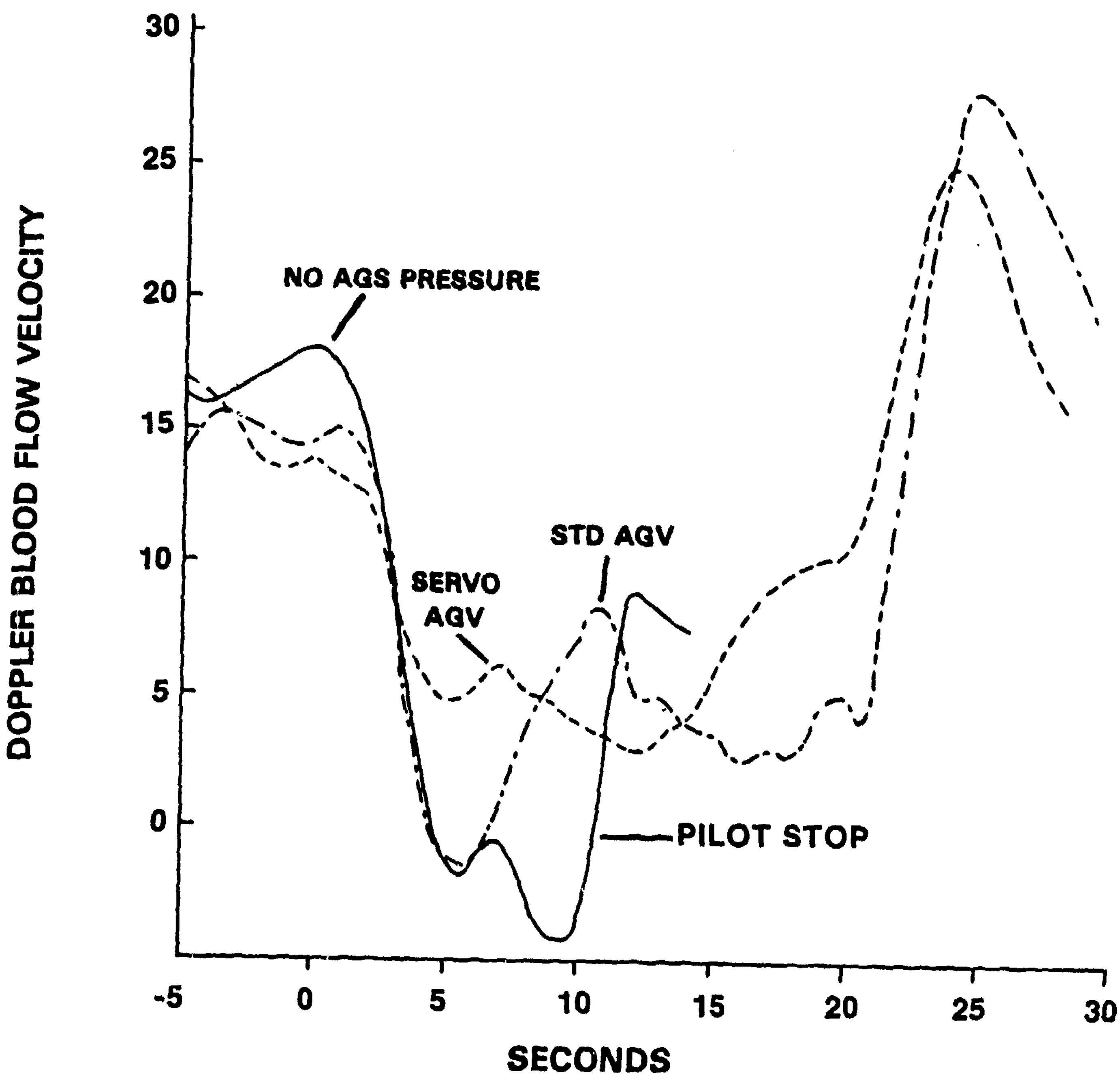

Figure 5. Effect Of Suit Pressure Schedule On Arterial Blood Velocity – 3.5 G 4 Sec Rise Time.

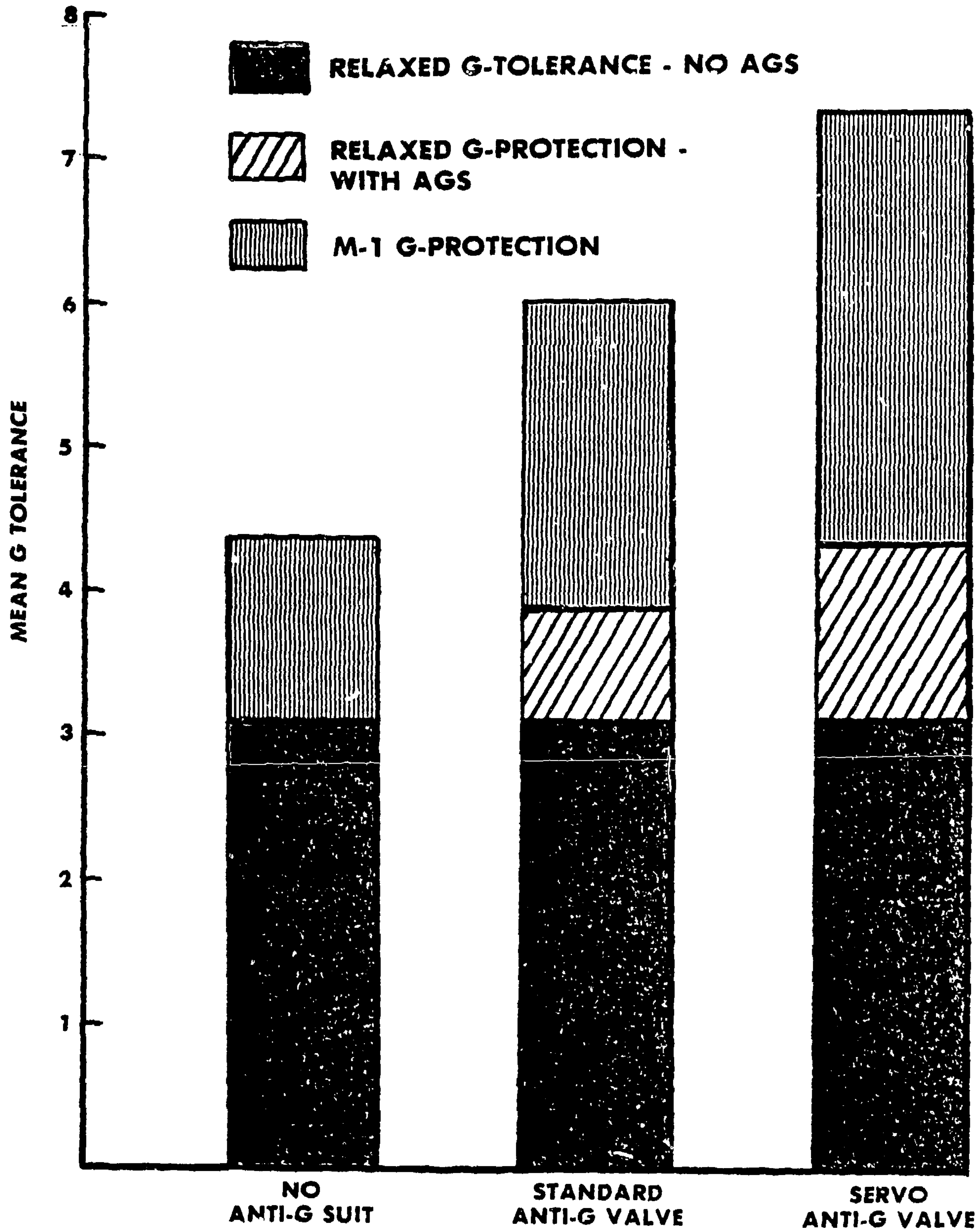

Figure 6. Mean PLL Tolerances For Each Of The Protective Techniques Used In The Study.

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